Description

Interface module for local data networks

The invention relates to an interface module for local data networks having at least one inductive component for coupling interface circuits to a data line used for connecting computers.

These types of modules are also referred to as LAN modules. Until now, ring cores made of highly permeable ferrite material (typically μ = 5,000) have been used for transformers and chokes in LAN interface modules. In order to achieve the necessary main inductance even with I_{DC} = 8 mA, with ferrites the number of turns must be designed high, typically 20 to 40 turns for 100 Mb/s ethernet transformers. The high number of turns leads to manufacturing technology disadvantages, e.g. in the implementation of the transformers in planar technology. In addition, LAN interface modules having ferrite cores occupy considerable space.

Furthermore, a requirement in LAN interface modules is that the main inductance maintains its value even at a maximum DC initial load of 8 mA in a temperature range from -40°C to 85°C, but preferably to 120°C. The permeability of the ferrites initially described, particularly of the MnZn ferrites, however, oscillates in the temperature range from -40°C to 120°C, sometimes by more than +/- 40%. These oscillations are undesirable.

The object of the present invention is therefore to provide interface modules having at least one inductive component which are suitable for use in local data networks and have a small structural volume as well as outstanding temperature stability of the permeability in the temperature range from -40°C to 120°C.

According to the invention, this object is achieved by an inductive component having a magnetic core made of an amorphous cobalt-based alloy or a nanocrystalline iron-based alloy having permeabilities $\mu > 30,000$.

The main frequency range of local data networks typically reaches up to 10 MHz (10 Mb/s ethernet) and/or up to 125 MHz (100 Mb/s ethernet) or, in the case of gigabit ethernet, even higher. As described above, if ferrite cores are used to achieve the necessary inductance at I_{DC} up to 8 mA, high numbers of turns are necessary.

This leads to high coupling and winding capacitances and to a large leakage inductance. These influences have a disadvantageous effect on the pulse shape, due to overshoots and large rise and fall times.

There is the possibility for amorphous and nanocrystalline alloys of setting the permeability very high through an appropriate manufacturing method, but this has the consequence that the magnetic cores are easily saturated. However, amorphous and nanocrystalline alloys are also easily set to average permeability values in the range from 12,000 to 80,000 and generally have a high saturation induction. It is therefore possible with nanocrystalline and amorphous alloys to tailor the geometric dimensions of a magnetic core, its permeability, and the number of turns to one another in such a way that small structural shapes become possible. It is to be particularly emphasized that the numbers of turns can be set to optimum values, so that simultaneously a low leakage inductance and winding capacitance result. Therefore, interface modules can be produced with amorphous and nanocrystalline magnetic cores which fulfill the requirements for the signal shape conforming to the standards and which are additionally distinguished by a particularly small structural volume and the possibility of economical manufacturing in planar technology.

Alloys particularly suitable for use in interface modules for local data networks are the object of the dependent claims.

In the following, the invention will be described in more detail with reference to the attached drawing.

Fig. 1   shows an overview of a part of a local data network;

Fig. 2   shows an exemplary embodiment of a circuit of inductive components in an interface module;

Fig. 3   shows a diagram which illustrates the dependence of the real part of the permeability in the serial equivalent network diagram for a nanocrystalline alloy and a ferrite;

Fig. 4   shows a diagram which illustrates the dependence of the inductance on the DC load in the parallel equivalent network diagram of a coil having a nanocrystalline magnetic core and of a coil having a ferrite coil;

Fig. 5   shows the temperature dependence of the permeability of amorphous and nanocrystalline alloys in comparison to the temperature dependence of the permeability of ferrites;

Fig. 6   shows the frequency response of the real part of the permeability of a nanocrystalline alloy in comparison to a ferrite;

Fig. 7   shows the frequency response of the inductance in the parallel equivalent network diagram for a coil having a magnetic core made of a nanocrystalline alloy and for coils having ferrite cores;

Fig. 8   shows the frequency response of the ohmic resistance in the parallel equivalent network diagram for a magnetic core made of a nanocrystalline alloy;

Fig. 9   shows the frequency response of the insertion loss which can be achieved with the nanocrystalline magnetic core from Figs. 7 and 8; and

Fig. 10   shows an example of a flat hysteresis loop of a
          magnetic core made of a nanocrystalline alloy.

Local data networks or LANs (local area networks) are used to
connect computers (PCs, workstations, mainframes) for data
transfer over short distances. LANs are differentiated according
to the transfer standard (IEEE 802.3, ethernet, IEEE 802.4
(token bus), IEEE 802.5 (token ring), transfer rates (e.g. 10
Mb/s, 100 Mb/s for ethernet), and physical transfer medium (RG58
coaxial cable, twisted pair, glass fiber, etc.). Computers can
be connected together via various topologies (star, bus, ring).
At the same time, as shown in Fig. 1, central units 1 such as
hubs, switches, bridges, and routers are necessary, as are
network cards 2 (NICs = network interface cards) in the
computers. To transmit the data in the physical layer, a logic
component 3 (component for the physical layer) is used in these
devices and cards, which is coupled to a LAN interface module 5
either directly or via a transmitter/receiver component 4
(transceiver). This LAN interface module 5 then produces the
connection to a data line 6.

An exemplary embodiment of the interface module 5 is shown in
Fig. 2. The interface module 5 in Fig. 2 comprises a transformer
7, as well as current compensated chokes 8, which each have
magnetic cores 9. The magnetic cores 9 may be made of the same
material or of different materials. In addition to the
components shown in Fig. 2, the interface module may have
further inductive components, such as transformer, choke, and
filter components.

In the following, we will restrict our description to LAN
interface modules 5 for 10 Mb/s and 100 Mb/s ethernet as
representative systems for all of these LAN technologies. The
main frequency range of the signals is < 10 MHz

for 10 Mb/s ethernet and < 125 MHz for 100 Mb/s ethernet. However, higher transfer rates (e.g. for gigabit ethernet) are also conceivable with the LAN interface modules 5 described here.

The following requirements are placed on the inductive components used in the LAN interface module 5:

    a) minimal structural volume

    b) suitability for the various transfer code systems, e.g.
        - MLT3 (100 Mb/s)
        - 4B5B (100 Mb/s)
        - Manchester coding (10 Mb/s)

    c) in accordance with ANSI X3.263-95 §9.1.7, the following must apply for 100 Mb/s ethernet:
       main inductance > 350 µH at 100 kHz, 100 mVrms, and 0 mA < I_{DC} < 8 mA

    d) in accordance with ANSI X3.263-95 §9.1.7, the following must apply for 100 Mb/s ethernet for the rise time t_{climb} and the fall time t_{fall} of the pulses: 3 ns < t_{climb}, t_{fall} < 5 ns

    f) low core weight and SMD capability

    g) ring core shape, therefore simpler safety requirements in accordance with IEC 950

    h) low insertion loss and high reflection loss (for 100 Mb/s ethernet in accordance with ANSI X3.263-95 §9.1.5) in the entire frequency range

    i) low and monotonic temperature response of the relevant magnetic characteristics in the range -40°C - 100°C.

The inductive components described here are inductive components for the LAN interface module 5 which contain the magnetic core 9 in the form of a small metal tape core made of amorphous or nanocrystalline alloy instead of a ferrite core. This core

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obtains its properties conforming to the standards through an optimized combination of tape thickness, alloy, and heat treatment in the magnetic field, as well as core technology manufacturing steps.

A first basic requirement is that the inductance of the LAN transformer 7 at 100 kHz is greater than 350 µH. This must be ensured in the entire temperature range from 0 to 70°C or even from -40°C to +85°C, possibly even from -40°C to +120°C, at a direct current of up to 8 mA. As Figs. 3, 4, and 5 show, this requirement was fulfilled, for example with nanocrystalline alloys, but also with amorphous alloys, with correctly tailored alloy, core dimension, and taping.

Fig. 3 is a diagram in which the real part of the permeability in the serial equivalent network diagram is plotted against the strength of the constant field. In this case, the solid curve illustrates the dependence of the real part of the permeability of the nanocrystalline alloy $(FeCuNb)_{77.5}(SiB)_{22.5}$, while the dashed curve indicates the dependence of the real part of the permeability of a MnZn ferrite with the trade name ("Ferronics B").

Fig. 4 shows the ideal inductance of the transformer 7 depending on the DC initial load. The solid curve represents the inductance of the transformer 5 having the magnetic core 9 made of the nanocrystalline alloy $(FeCuNb)_{77.5}(SiB)_{22.5}$ for an initial permeability $\mu_1(p) = 40,000$ and 9 turns. The dashed line is the ideal inductance of a transformer having a MnZn ferrite core ("Ferronics B") with an initial permeability of $\mu_1 = 5,000$ and 20 turns. It can be seen from Fig. 4 that the transformer 5 having the magnetic core 9 made of the nanocrystalline alloy fulfills the requirements significantly better than the transmitter with the ferrite core, in spite of the low number of turns.

In Fig. 5, the relative change in permeability in percent in relation to the permeability at room temperature is plotted for various materials. A first sharply rising curve represents the temperature change of a MnZn ferrite with the trade name "Siferrit N27". The permeability of a further MnZn ferrite ("Ferronics B") oscillates in the temperature range from -40 to 120°C by more than +/- 40%. The relative change in permeability for the nanocrystalline $Fe_{73.5}Cu_1Nb_3Si_{15.5}B_7$ and the amorphous $(CuFi)_{72}(MuMnSiB)_{28}$, in contrast, is in the range from +/-20%.

Furthermore, one can see in Figs. 6 and 7 that in the LAN transformer 5 having a metal tape core, unlike one having a ferrite core, no resonances arise (Fig. 6), and resonances caused by the winding capacitance first occur at the upper edge of the signal spectrum due to the lower number of windings (Fig. 7) and therefore—in comparison to ferrite—have a smaller phase shift of the signal as a consequence. This can have an effect on the effective bit rate, since fewer bit errors have to be corrected by the transfer protocol used.

A second basic requirement is that the insertion loss a_E of the transformer 7 is as low as possible over the entire frequency range. With the magnetic cores 9 described here, a_E values of significantly under 1 dB can be achieved at $f \geq 100$ kHz. For a predetermined wave impedance (in this case 100 Ω), the insertion loss falls with an increasing value of R_p. In this case, R_p is the ohmic resistance in the parallel equivalent network diagram for the transformer 7, which represents the hysteresis losses in the magnetic core 9 and the ohmic copper losses of the taping. Using electrodynamics, the relationship

$$R_p(f) = 2 * \pi^2 * N^2 * (1/\rho_{mech}) * (A_{Fe}/l_{Fe}) * f^2 * B^2 / P_{Fe}(f) \qquad (1)$$

can be derived with the density ρ_{mech}, with $P_{Fe}(f)$ representing the frequency response of the specific overall losses, which in

turn depends on the hysteresis and tape properties. However, for the frequencies of more than 100 kHz and extremely linear hysteresis loops considered here, only tape-dependent eddy current losses and gyromagnetic effects still play a role.

As can be seen from Figs. 8 and 9, sufficiently small a_E values and/or sufficiently large R_p values can be achieved with the heat-treated magnetic alloys used here, even with the low number of turns desired in this case. Also, as can easily be reconstructed with reference to equation (2), particularly high R_p values can be achieved with the lowest possible tape thicknesses of ≤ 20 µm, preferably ≤ 17 µm, or as much as possible even ≤ 14 µm. The R_p value can be improved even further by coating at least one tape surface with an electrically insulating medium, which must have a low relative permittivity of $\varepsilon_n < 10$.

A third basic requirement is that the leakage inductance L_s of both the transformer 7 and the current-compensated chokes 8 is as small as possible. This is from the requirements of ANSI X3.263 1995 points 9.1.3 (overshoot of the signal), 9.1.6 (rise times of the signal), and 9.1.5 (reflection loss requirements). A large leakage inductance has overshooting and a large rise time of the signal as a consequence. For higher signal frequencies, the reflection loss is reduced by a large leakage inductance. Due to the core geometry used (ring tape core) and the low number of turns possible due to higher permeability, very small leakage inductances can be achieved—in contrast to ferrites.

Overall, it can be established that through the combination of flat hysteresis loops and, compared with ferrite solutions, significantly higher permeability µ and saturation induction B_s, inductors for LAN interface modules having particularly low numbers of turns and smaller structural sizes can be produced

using thin tapes of the heat-treated alloys used here having
high specific electrical resistance.

In the experiments which this is based on, it was recognized
that the properties conforming to the standards of the small
magnetic cores 9 of inductors used in the LAN interface modules
could be achieved with amorphous cobalt-based alloys almost free
of magnetostriction and with fine crystalline alloys practically
free of magnetostriction. The latter are typically referred to
as "nanocrystalline alloys" and are characterized by an
extremely fine grain with an average diameter of less than
100 nm, which occupies more than 50% of the material volume. An
important requirement is that the inductors have a high
saturation induction of $B_s > 0.55$ T, preferably > 0.9 T, more
preferably > 1 T, and a very linear hysteresis loop with a
saturation to remanence ratio of $B_r/B_s < 0.2$, preferably < 0.08.
In this connection, the nanocrystalline materials based on iron
which are free of magnetostriction are distinguished by a
particularly high saturation induction of 1.1 T or more. A list
of all of the alloy systems considered and found suitable
according to the invention is found below. A typical loop shape
can be seen in Fig. 10. Such a hysteresis loop can, for example,
be achieved by the manufacturing procedures described in the
following:

The soft-magnetic amorphous tape, produced by means of rapid
solidification technology, with a thickness $d \leq 22$ µm,
preferably ≤ 17 µm, more preferably ≤ 14 µm, made of one of the
alloys listed below, is wound tension-free on special machines
into the magnetic core 9 in its final dimension. Alternatively,
magnetic cores 9 which are constructed from a stack of stamped
disks made of the alloys mentioned could also be considered in
this case.

It was found that the requirements conforming to the standards
for the frequency properties could be fulfilled even better if
the tape is coated on one or two sides with an electrically
insulating material before the winding of the magnetic core 9,
particularly before the stamping of the disks. For this purpose,
depending on the requirements for the quality of the insulating
film, an oxidation, immersion, pass-through, spray, or
electrolysis method is used on the tape. The same effect can,
however, also be achieved by immersion insulation of the wound
or stacked magnetic core 9. In the selection of the insulating
medium, care should be taken that, on one hand, it adheres well
to the tape surface, and, on the other hand, it does not cause
any surface reactions which could lead to damage of the magnetic
properties. For the alloys used in this case according to the
invention, oxides, acrylates, phosphates, silicates, and
chromates of the elements Ca, Mg, Al, Ti, Zr, Hf, and Si have
been shown to be effective and compatible insulators.
Particularly effective, but still gentle in this case is Mg,
which is applied as a liquid preproduct containing magnesium to
the tape surface, and which transforms into a dense film of MgO,
whose thickness can be between 50 nm and 1 µm, during a special
heat treatment which does not influence the alloy.

During the subsequent heat treatment of the insulated or
uninsulated magnetic core 9 to set the soft-magnetic properties,
it is to be differentiated whether the magnetic core 9 is made
of an alloy which is suitable for achieving a nanocrystalline
structure or not.

Magnetic cores 9 made of alloys which are suitable for
nanocrystallization are subjected to an exactly tailored
crystallization heat treatment, which lies between 450°C and
690°C depending on the alloy composition, to achieve the
nanocrystalline structure. Typical dwell times are between
4 minutes and 8 hours. Depending on the alloy, this

crystallization heat treatment is to be performed in vacuum or in a passive or reducing protective gas. In all cases, material-specific purity conditions are to be considered, which are to be produced by appropriate aids such as element-specific absorber or getter materials, depending on the case. At the same time, through an exactly balanced combination of temperature and time, the fact is exploited that with the alloy compositions used here, described below in more detail, the magnetostriction contributions of fine crystalline grain and amorphous residual phase precisely offset one another and the necessary freedom from magnetostriction ($|\lambda_s| < 2$ ppm, preferably even $|\lambda_s| < 0.2$ ppm) arises. The high permeabilities desired in this case require these particularly exactly equalized magnetostriction values and thus a particularly exactly adjusted grain size distribution, and therefore alloy composition. Exact control of the magnetic core temperature in the range of crystal formation is important in this case. In any case, the material may not be heated so much that irreversible damage of the magnetic properties arises due to the formation of nonmagnetic phases, such as Fe borides.

Depending on the alloy and embodiment of the component, annealing is either performed without a field or in a magnetic field lengthwise to the direction of the wound tape (``longitudinal field'') or transverse to this (``transverse field''). In specific cases, a combination of two or even three of these magnetic field configurations may also be necessary in sequence or parallel to one another.

The magnetic properties, i.e., the linearity and the slope of the hysteresis loops may—if necessary—be varied within a wide range by an additional heat treatment in a magnetic field which is parallel to the rotational symmetry axis of the magnetic core 9 —i.e., perpendicular to the tape direction. Depending on the alloy and permeability level to be set, which depends on the

dimension, temperatures between 350°C and 690°C are necessary in this case. Due to the kinetics of the atomic reorientation procedures, the resulting permeability values are normally higher the lower the transverse field temperature applied. This magnetic field heat treatment is either combined directly with the crystallization heat treatment or performed separately. The same conditions apply for the annealing atmosphere as in the annealing to achieve the nanocrystalline structure.

In magnetic cores 9 made of amorphous materials, the setting of the magnetic properties, i.e., of the curve and slope of the linear flat hysteresis loop, is performed by a heat treatment in a magnetic field which runs parallel to the rotational symmetry axis of the magnetic core 9—i.e., perpendicular to the tape direction. Through favorable control of the heat treatment, the fact is exploited that the value of the saturation magnetostriction changes during the heat treatment in the positive direction by an amount which depends on the alloy composition until it reaches the range $|\lambda_s| < 2$ ppm, preferably even $|\lambda_s| < 0.05$ ppm. As table 2 shows, this was also achieved when the amount of λ_s was well over this value in the "as quenched" state of the tape. Depending on the alloy used, flushing of the magnetic core 9 either with air or a reducing protective gas (e.g. NH_3, H_2, CO) or a passive protective gas (e.g. He, Ne, Ar, N_2, CO_2) is important in this case so that neither oxidation nor other reactions may occur on the tape surfaces. Solid-state physical reactions due to protective gas which diffuses in may also not occur inside the material.

Depending on the position of the Curie temperature and the crystallization temperature of the alloy used, the magnetic cores 9 for the inductors used in the LAN interface modules 5 can be heated to a temperature between 180°C and 420°C under an applied magnetic field at a rate of 0.1 to 10 K/min, kept at this temperature in the magnetic field for between 0.25 and 48

hours, and subsequently cooled back to room temperature at 0.1-5 K/min. Due to the general relationships $K_u \propto M_s(T_a)^2$ and $K_u \propto 1/\mu$ (K_u = anisotropy energy, M_s = saturation magnetization, T_a = starting temperature in the magnetic field), the loops achieved with the amorphous alloys used here are flatter the higher M_s is. Consequently, one is in a dilemma, in which high permeabilities and high saturation inductions, which are, however, indispensable for high asymmetric currents, mutually exclude one another.

Particularly small magnetic cores 9 for LAN transformers 7 can be achieved if the amorphous alloys used have, on one hand, low Curie temperatures of, for example, less than 250°C, but, on the other hand, still have a sufficiently high saturation induction of, for example, 0.65 Tesla or more. Such combinations, which are contradictory in principle, can be achieved in that the metalloid content (e.g. Si, B, etc.) in the alloy is elevated gradually, and/or an antiferromagnetic element, such as Mn, is simultaneously added to the alloy in the range of a few at%. As a consequence of smaller magnetic moments with, at the same time, temperature-conditioned delay of the reorientation kinetics, particularly small uniaxial (transverse) anisotropies of only 1 J/m^3 or even less can then be achieved below the Curie temperature by means of defined cooling in the transverse field, and therefore permeability values of, for example, 20,000 to 200,000.

An important requirement for reaching these types of high permeabilities is that all types of interference terms, such as magnetoelastic anisotropies, are negligible relative to the desired anisotropies induced by the magnetic field. To fulfill this requirement, the wound magnetic core 9 in the form of a metal tape core must be relaxed by means of a relaxation annealing, even at the smallest magnetostriction values. The temperature necessary for this purpose is to be set sufficiently

high that, on one hand, the relaxation kinetics proceeds
sufficiently rapidly, but, on the other hand, no crystallization
occurs yet. Particularly high effectiveness may be achieved
with this procedure if the crystallization and Curie
temperatures are different from one another by much more than
100°C, which is precisely the case in the amorphous alloys with
a high metalloid content used here.

In some cases, a temperature plateau in the transverse field can
be introduced in addition to the slow cooling of the magnetic
cores 9 in the transverse field to elevate the uniaxial
anisotropy energy. Following the known influence of temperature
dependence of the saturation magnetization and reorientation
kinetics, the decisive parameters in this case are the optimum
interval to the Curie temperature and the dwell time until the
equilibrium value of the uniaxial anisotropy is reached
asymptotically, which are to be tailored to the respective
alloy.

Due to the demagnetizing fields inside a magnetic core stack,
which lead to a significant weakening and a divergence of the
field lines, sufficiently linear loops can be achieved even with
high permeability values in that the magnetic cores 9 are
stacked exactly on their faces during the transverse field
treatment in such a way that the stack height is at least 10
times, preferably at least 20 times, the magnetic core outer
diameter. This applies in the same way for nanocrystalline and
for amorphous magnetic materials. A typical magnetization curve
which emphasizes the linear character of the loops implemented
in this way can be seen in Fig. 10.

Following the heat treatment, the magnetic cores 9 are
electrically insulated (e.g. surface passivated, coated, whirl
sintered, or encapsulated in a plastic housing), provided with
the primary and/or secondary windings, and possibly glued or

embedded in the component housing. In this case, there is also the possibility of using a design in so-called planar technology. This method is independent of whether the magnetic core 9 is made of amorphous or nanocrystalline material. However, the mechanical handling of the annealed nanocrystalline magnetic core 9 must be performed with particular care because of its brittleness.

A further manufacturing possibility is that the tape is first subjected to a transverse field tempering as it passes and is subsequently wound into the tape core. The further sequence runs as described above.

The essential requirements for 10/100 BaseT transformers fulfilled in this case are:

- The main inductance of the magnetic core 9 in the form of a wound metal tape core must fulfill the following condition in accordance with ANSI X3.263 1995:
  $L_h > 350$ µH at 100 kHz.
- Sufficiently high values of over > 1 kΩ may be achieved for the resistance R_p in a parallel equivalent network diagram, even with low numbers of turns.
- The main inductance fulfills this value even at a maximum DC initial load of 8 mA in a temperature range from −40° to 85°C, or even up to 120°C if nanocrystalline alloys are used.
- The linearity error of the hysteresis loop of the magnetic core 9 is so low that for the ratio of permeability μ to the average permeability $\bar{u}$ in the range $B_s/100$ to $0.8 \, B_s$, the following relationship applies:
  $1.2 > \mu(B)/ \, \bar{u} > 0.8$, preferably $1.1 > \mu(B)/ \, \bar{u} > 0.9$, with B also lying in the interval $B_s/100$ to $0.8 \, B_s$.
- Using amorphous and nanocrystalline magnetic materials, after balanced transverse field annealing, the typical dimensions of the magnetic core 9 shown in table 1, for example, result for predetermined values of the main inductance, with the dimensions being given in the sequence

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outer diameter, inner diameter, and height of the magnetic
core 9 provided in the form of a ring tape core.

L_{main} [µH]	R_p [Ω]	number of turns N	core dimension [mm^3]	core mass [g]	material
830	> 1 kΩ	9	6.0*2.0*2.0	0.3	$Fe_{73.5}Cu_1Nb_3Si_{15.5}B_7$
830	> 1 kΩ	9	6.0*2.0*2.0	0.3	$Co_{68.25}Fe_{3.35}Mn_1Si_{15.4}B_{11}$
830	> 1 kΩ	11	4.0*2.0*2.0	0.1	$Fe_{73.5}Cu_1Nb_3Si_{15.5}B_7$
830	> 1 kΩ	11	4.0*2.0*2.0	0.1	$Co_{68.25}Fe_{3.35}Mn_1Si_{15.4}B_{11}$

Similar dimensions of the magnetic core 9 also result upon the
use of the other alloys listed below, which can be used
depending on the application.

An array of relationships must be considered in the dimensioning
of the inductive components of the interface module 5,
particularly of the transformer 7.

The relationship

$$L = N^2 \mu_o \mu_r A_{Fe}/l_{Fe} \qquad (2)$$

applies for the inductance of the transformer 7, with

N = number of turns
μ_o = universal permeability constant
μ_r = permeability of the material
A_{Fe} = iron cross-section of the magnetic core
l_{Fe} = iron path length of the magnetic core.

From equation (2), it is obvious that the necessary inductance
can only be achieved with minimum structural volume if the
number of turns, permeability, core cross-section, and iron path
length are tailored to one another. The permeability µ of the

core material, applicable over the entire range of the operating frequency, is, besides the favorable ring-shaped geometry, the decisive parameter for the most compact possible dimension of the transformer 7. Depending on which of the following alloys listed is used and how the associated heat treatment is performed, a permeability range between 10,000 and more than 100,000 can be covered in a defined way. The LAN interface modules 5 implemented with these magnetic cores 9 have a strong advantage in volume relative to the ferrite cores due to their construction, the high permeability, and the high saturation induction of the metal tape cores used.

A fundamental restriction arises in the selection of the core material for the inductors of the transformer 7 in that the magnetic core 9 may not reach saturation at the DC initial load of 8 mA. Furthermore, the distortion factor at maximum I_{DC} modulation must remain under limits established in accordance with the standards. The magnetic field strength H_{DC} connected with the I_{DC} initial load is given by

$$H_{DC} = N * I_{DC}/l_{Fe} \qquad (3)$$

The inductance and the distortion factor may only fall very slightly in the entire temperature range at this DC initial load.

In contrast to the inductive components with ferrites, in which equation (2) determines the numbers of turns, equation (1) is decisive for the dimensioning of inductive components with nanocrystalline or amorphous metal cores. Specifically, the number of turns N selected may not be too small, since otherwise the insertion loss will be too large due to the too small R_p resistance of the transformer 7. In addition, small numbers of turns have high leakage inductances as a consequence, which cause an overshoot and a large rise time of the signal. An

elevation of the number of turns also leads to a smaller signal modulation B_{ac} and therefore to a lower distortion factor. The transformer 7 thus preferably has average numbers of turns between 5 and 25 turns.

This situation requires a combination of high saturation induction B_s, high permeability μ, and low core losses ($\sim 1/R_p$) during the material selection.

A high permeability and therefore a low number of turns, as well as the ring tape shape of the magnetic core 9, leads to small transformers 7 with low leakage inductances and small coupling and winding capacitances. In turn, this leads to shorter rise times, better asymmetrical loss, and improved transient response in the entire frequency range.

In the following, several suitable alloy systems are described in more detail. It was found that with the alloy systems described in the following, if the conditions described above were maintained, inductive elements for the interface modules 5 with particularly linear hysteresis loops and small structural shapes could be produced which had all the properties conforming to the standards.

It should be noted that in the description of the alloy systems listed below, the greater than/less than signs enclose the limits; in addition, all at% information should be considered approximate.

Alloy system 1:

A first alloy system has the composition $Co_a(Fe_{1-c}Mn_c)_bNi_dM_eSi_xB_yC_z$, with M indicating one or more elements from the group Nb, Mo, Ta, Cr, W, Ge, and/or P and $a+b+d+e+x+y+z = 100$, with

Co: $a = 40 - 82$ at%, preferably $55 < a < 72$ at%,

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Fe+Mn:  b = 3 - 10 at%,
Mn/Fe:  c = 0 - 1,          preferably x < 0.5,
Ni:     d = 0 - 30 at%,     preferably d < 20 at%,
M:      e = 0 - 5 at%,      preferably e < 3 at%,
Si:     x = 0 - 18 at%,     preferably x > 1 at%,
B:      y = 8 - 26 at%,     preferably 8 - 20 at%,
C:      z = 0 - 3 at%,
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$15 < e+x+y+z < 30$, preferably $20 < e+x+y+z < 30$.

Alloys of this system remain amorphous after the heat treatment described. Depending on the composition and heat treatment, extremely linear hysteresis loops having a very wide permeability range between 500 and 150,000 or even more can be implemented with this system.

For the present invention, it has proven particularly important that the value of the saturation magnetostriction can be reliably set to particularly small values of $|\lambda_s| < 0.1$ ppm with a heat treatment tailored to the alloy composition. A particularly linear loop shape results in this way, which leads to a particularly high consistency of the permeability over a wide induction range. In addition, the occurrence of damaging magnetoelastic resonances of the ring tape magnetic core 9 are avoided by this. At specific frequencies of the induction curve, these may lead to breaks in the permeability or to elevated hysteresis losses. During the experiments it was discovered that precisely the combination of this near freedom from magnetostriction, a tape thickness which was as low as possible (preferably less than 17 μm), and a comparatively high specific electrical resistance of 1.1 to 1.5 μΩm leads to extremely good frequency response, which is particularly suitable for the transformer 7.

Alloy system 2:

A second alloy system has the composition $Fe_xCu_yM_zSi_vB_w$, with M indicating an element from the group Nb, W, Ta, Zr, Hf, Ti, Mo, or a combination of these and $x + y + z + v + w = 100\%$, with

Fe:	$x = 100\% - y - z - v - w$,	
Cu:	$y = 0.5 - 2$ at%,	preferably 1 at%,
M:	$z = 1 - 6$ at%,	preferably $2 - 4$ at%,
Si:	$v = 6.5 - 18$ at%,	preferably $14 - 17$ at%,
B:	$w = 5 - 14$ at%,	preferably $6 - 9$ at%

with $v + w > 18$ at%, preferably $v + w = 20$ to 24 at%.

Alloys of this system have been shown to be very suitable for the transformer 7 due to their linear loop shape and their very good frequency response. Particularly good properties are achieved in the alloy compositions designated with "preferably", since in this case, just as in the alloy system 1, a zero crossing of the saturation magnetostriction may be achieved. At the same time, it was also found out that precisely the combination of a high specific electrical resistance of 1.1 to 1.2 μΩm and a low tape thickness lead to outstanding frequency response, which can be further increased by reduced tape thicknesses of 14 μm or even less. As can be seen from Fig. 3, at 100 kHz initial permeabilities of $\mu_1(100 \text{ kHz}) > 25,000$ can be maintained with optimally tuned heat treatment without problems, in some cases, $\mu_1 > 50,000$ were even observed in the experiments performed in this case.

The comparatively high saturation induction for extremely linear loops, measured at $B_S = 1.1 - 1.3$ T, has also been shown to be very advantageous, since in this way a high stability in regard to asymmetrical currents arises. Furthermore, high values for the gyromagnetic limiting frequency, which ultimately depends on B_s/μ_1, are achieved. The latter is an important requirement for high permeabilities in the MHz range. In addition, it was found that the temperature characteristic of the magnetic cores 9 may

be adjusted in a targeted way by means of the heat treatment for setting the permeability. From this, precisely in rough environmental conditions, which can certainly occur in telecommunication devices, advantages specific to an application which cannot be implemented in other ways may arise.

Alloy system 3:

A third alloy system suitable for has the composition $Fe_xZr_yNb_zB_vCu_w$, with $x + y + z + v + w = 100$ at%, with

Fe:	$x = 100$ at% $- y - z - v - w$, preferably $83 - 86$ at%,
Zr:	$y = 2 - 5$ at%, preferably $3 - 4$ at%,
Nb:	$z = 2 - 5$ at%, preferably $3 - 4$ at%,
B:	$v = 5 - 9$ at%,
Cu:	$w = 0.5 - 1.5$ at%, preferably 1 at%,

with $y + z > 5$ at%, preferably 7 at%,
and $y + z + v > 11$ at%, preferably $12 - 16$ at%.

With alloys of this system, linear loop shapes with permeabilities between approximately 12,000 and more than 30,000 are achieved through transverse field heat treatments, which are to be performed alloy-specific in the interval between 510°C and 680°C. At tape thicknesses of around 15 μm, initial permeabilities of nearly 20,000 are still present at 100 kHz and therefore a good frequency response, suitable for the inductive components in the interface module 5. The high saturation induction of approximately 1.5 to 1.6 T also has a particularly favorable effect on the size of the component and the position of the gyromagnetic limiting frequency in this case. The very small saturation magnetostriction, which was significantly below $|\lambda_s| = 1$ ppm at initial temperatures around 600°C, should be particularly emphasized here.

Alloy system 4:

A fourth alloy system has the composition $Fe_xM_yB_zCu_w$, with M indicating an element from the group Zr, Hf, Nb and x + y + z + w = 100 at%, with

Fe:	x = 100 at% - y - z - w, preferably, 83 - 91 at%,
M:	y = 6 - 8 at%,	preferably 7 at%,
B:	z = 3 - 9 at%,
Cu:	w = 0 - 1.5 at%.

The basic requirement of $|\lambda_s| < 1$ ppm may be fulfilled with alloys of this system. The alloy-specific permeabilities which may be achieved with the transverse field treatments performed between 510°C and 680°C are between 2,000 and 15,000. The high saturation induction of 1.5 to 1.6 T also allows the implementation of very small interface modules 5.

Alloy system 5:

A fifth alloy system has the composition $(Fe_{0.98}Co_{0.02})_{90-x}Zr_7B_{2+x}Cu_1$, with x = 0 - 3, preferably x = 0, with the residual alloy component Co able to be replaced by Ni with appropriate equalization.

With this system, a zero crossing in the saturation magnetostriction may also be achieved with alloy-specific tailored transverse field heat treatment, which allows particularly linear hysteresis curves at starting permeabilities of $\mu_1 > 10,000$. In this way, the frequency responses of the complex permeability become so good that they come very close to those of alloy systems 1 and 2. The high saturation induction, which has values around $B_s = 1.70$ T, is an outstanding advantage of this system.

Through the particularly favorable combination of near freedom from magnetostriction and high saturation induction, interface modules 5 with particularly small structural shapes may again be implemented.

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The alloy systems 2 to 5 obtain a fine crystalline structure
with grain diameters under 100 nm after the heat treatment.
These grains are surrounded by amorphous phase which, however,
occupies less than 50% of the material volume.

All of the alloy systems 1 to 5 are distinguished by the
following properties:

- very linear hysteresis loops;

- amount of the saturation magnetostriction $|\lambda_s|$ < 2 ppm,
  preferably < 0.1 ppm after the heat treatment. In the cobalt-
  based amorphous materials, this is to be set by fine-tuning
  the Fe and Mn content appropriately. In the nanocrystalline
  alloys, this is to be set via the size of the fine crystalline
  grain, which may be produced by a targeted adjustment of the
  heat treatment, the metalloid content, and the content of
  refractory metals.

- saturation induction of 0.56 T - 1.7 T. The saturation
  induction may be fine-tuned by selection of the content of Ni,
  Co, M, Si, B, and C.

- tapes whose thickness can be less than 17 μm;

- high specific electrical resistance, which can be up to 1.5
  μΩm.

Examples:

The requirements and alloy ranges described above were
maintained and/or fulfilled after performing the heat treatment
described, e.g. through the exemplary alloys listed in table 2.

Table 2

Alloy composition [at%]	structure	saturation induction [T]	starting permeability μ_1	saturation magnetostriction	
				as quenched	heat-treated
$(CoFe)_{72}Mo_{1.5}(SiB)_{26.5}$	amorphous	0.57	50,000... 130,000	$-12*10^{-8}$	$-1.3*10^{-8}$
$(CoFeMn)_{74}(SiB)_{26}$	amorphous	0.65	25,000... 60,000	$-15*10^{-8}$	$-2.1*10^{-8}$
$Fe_{73.5}Cu_1Nb_3Si_{15.5}B_7$	nanocr.	1.21	20,000... 150,000	$+24*10^{-6}$	$+1.6*10^{-7}$
$Fe_{84}Zr_{3.5}Nb_{3.5}B_8Cu_1$	nanocr.	1.53	12,000... 30,000	$+3*10^{-6}$	$+1.5*10^{-7}$

The amorphous, fine crystalline, or nanocrystalline alloys listed in table 2 are distinguished by particularly high values of the saturation induction of up to 1.7 Tesla. This allows comparatively high permeability values, which produces further advantages in regard to overall size and taping relative to ferrite transformers.